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Deep Bore Hole Instrumentation Along San Francisco Bay Bridges

Lawrence Hutchings, Paul Kasameyer, William Foxall, Jennifer Hollfelder and Christine Turpin;
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Steven Jarpe, Institute of Crustal Studies; Santa Barbara, CA
William Bakun; United States Geological Survey (USGS)

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environmental

Abstract

The Bay Bridges down hole network consists of sensors in bore holes that are drilled 100' into bedrock around and in the San Francisco Bay. Between 2 and 8 instruments have been spaced along the Dumbarton, San Mateo, Bay, and San Rafael bridges. The instruments will provide multiple use data that is important to geotechnical, structural engineering, and seismological studies. The holes are between 100 and 1000 ft deep and were drilled by Caltrans. There are twenty-one sensor packages at fifteen sites. Extensive financial support is being contributed by Caltrans, UCB, LBL, LLNL-LDRD, U.C. Campus/Laboratory Collaboration (CLC) program, and USGS. The down hole instrument package contains a three component HS-1 seismometer and three orthogonal Wilcox 731 accelerometers, and is capable of recording a micro g from local M =1.0 earthquakes to 0.5 g strong ground motion form large Bay Area earthquakes.

Introduction

The Bay Bridges down hole network consists of recordings in bore holes that are drilled 100 ft into bedrock along and in the San Francisco Bay (Figure 1). Between 1 and 8 instruments have been spaced along the Dumbarton, San Mateo, Bay, Carquinez, and San Rafael bridges. Tables 1 - 5 list recording site information, and Figures 2 - 6 show profile locations of the instrument locations. In addition, two vertical arrays exist at the Dumbarton bridge with additional sensors at the surface and at 200 ft (Table 1). Two sensors are currently located at the surface at the Bay Bridge and are waiting drill holes. Prior to this study few seismic recording instruments existed in bedrock in San Francisco Bay. This left a recording gap for engineering studies of the Bay bridges and in seismicity studies of the Bay Area. Figures 7 and 8 show earthquakes recorded by instruments along the Bay and Dumbarton bridges. The Bridges network is part of a larger Hayward Fault Digital Network, see Figure 9.

There are six primary areas of research by LLNL that will be enhanced by the bore hole instrumentation: 1) developing realistic predictions of strong ground motion at multiple input points along long span bridges, 2) examining ground motion variability in bedrock, 3) calibrating soil response models, 4) developing bridge response calculations with multiple support input motions, 5) evaluate the seismicity of potentially active faults in the San Francisco Bay, and 6) record strong ground motion.

Key to these studies is LLNL's effort to exploit the information available in weak ground motions (generally from earthquakes < M=3.0) to enhance predictions of seismic hazards. Although strong ground motion recordings are essential to calibrate models and understand the hazard of future earthquakes, we can obtain weak ground motion data immediately, whereas it may be years before strong motion data is recorded. Following is an expansion of research goals utilizing recordings from the Bridges Network.

1) prediction of strong ground motion: LLNL is developing a methodology of using weak ground motion to synthesize linear response strong ground motion and incorporating this with constraints on fault rupture scenarios to predict strong ground motion. These computations provide estimates of the full wavetrain ground motion at multiple points along long span structures.

2) ground motion variability: Recent studies have demonstrated the high variability of strong ground motion with site conditions. Recordings along Bay bridges will be used both to improve calculations of ground motions for bridges, and to research the spatial sensitivity and significance of site variability to structures.

3) soils response: LLNL is researching means of using weak ground motion to constrain soils models for non-linear computations. Current research has shown that low strain constitutive properties are significant to non-linear ground motion computations, and that these values can be significantly improved by an iterative process of matching weak motion solutions.

4) bridge response calculations: Current developments in structural dynamics allow non-linear, three-dimensional calculation of bridge response. This requires realistic full wavetrain input ground motions. LLNL is conducting research on the sensitivity of synthetic ground motions to accurate non-linear computations, and the significance of utilizing multiple support input calculations.

5) seismicity: Location of small earthquakes within the Bay that may indicate the existence of active faults will be made possible with the instrumentation. Very small earthquakes ($M<2$) cannot be recorded adequately to determine accurate locations by regional networks.

6) *strong ground motion:* Strong ground motion from previous earthquakes gives a good indication of what might be expected from future earthquakes. In addition recent earthquakes have demonstrated the high variability of strong ground motion so that an array of strong ground motion recordings will give a better understanding of the ground motion variability from future earthquakes.

Instrumentation

The down-hole sensor package is manufactured at LBL under the direction to Dr. Tom McEvilly, and is the same package used by the USGS and LBL for the Hayward Fault Digital Recording Network. This package contains three orthogonal Oyo HS-1 4.5 Hz geophones and a three orthogonal Wilcoxon 731s 10v/g accelerometers. The dynamic range of the Wilcoxon package is from a micro-g to 0.5 g acceleration, and is flat to frequency response from 0.1 to 300 Hz. This allows recording of M =1.0 to 0.5 g strong ground motion form large Bay Area earthquakes. Typically, the Wilcoxon's are recorded over two dynamic ranges to capture weak and strong ground motions, and HS-1's are used as a backup for weak ground motion recording. A Portable Data Acquisition System (DAS) is used to record the data. The DAS are 16 bit Refraction Technology 72A series seismographs is used for most sites. Three site utilize Quantera-4120 recorders. The signals are sampled at 200 sps. The data is processed and managed at UC Berkeley.

Geology of San Francisco Bay

San Francisco Bay is composed of two distinct units; bedrock and a younger unconsolidated sediment sequence which can be further subdivided into the Alameda formation (oldest), San Antonio formation, Posey formation, Merritt formation and the Bay Mud (youngest). Figure 10 shows the subsurface geology beneath the San Francisco- Oakland Bay Bridge. (Trask, P. and Rolston, R., 1951, *Engineering Geology of San Francsisco Bay, California*: Bull. Geol. Soc. Am.: v. 62, pp. 1079-1110.)

Unit	Geologic Characteristics
Bedrock	Composed of the Franciscan formation (Mesozoic). The Franciscan formation contains interbedded feldspathic sandstone, graywacke, siltstone, shale, limestone, radiolarian chert, metavolcanic rocks, and glaucophane schists. The total thickness of this unit is unknown but has been estimated to be at least 10,000 feet thick and at most 50,000 feet thick. (Figure 11).
Alameda formation	Composed of layers of firm sand, silt, clay, and fine gravel. The formation commonly appears gray but can be greenish gray or brownish gray. The gravel contains well rounded pebbles (up to 1in in diameter) from the Franciscan formation. Plant fragments can be found throughout the unit but seem to be heavily concentrated within the upper portion. On the west side of the San Francisco Bay, at a depth of ~280 feet, a layer of clean white volcanic ash is interbedded within the unit. The volcanic ash is a dacitic vitric tuff which contains 10% crystals (feldspar, hornblende, quartz) and 90% glass.
San Antonio formation	The unit can be divided into three distinct layers. The first layer consists of a firm silty clay. The second layer contains fine- to medium-grained sand and silty clay with shell fragments. The second layer is not found on the western side of the San Francisco Bay. The third layer is composed of gray to greenish gray fine grained clay with interbedded layers of sand or sandy gravel containing Franciscan pebbles. This layer contains a continuous bed of plant fragments near the base.

Acknowledgement: Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

Table 2: Bay Bridge Recording sites

i.d.	sensors	latitude	longitude	depth (m)	sensor h1, h2 + 090	Recording
E07	Wil-731A,HS-1	37.81847	122.34688	-----	------	2/96-present
E17	Wil-731A,HS-1	37.82086	122.33534	159.7	------	8/95-present
E23 (BBEB)	HS-1	37.82167	122.32867	150	------	3/94-10/95

Table 3: San Rafael Bridge Recording sites

i.d.	sensors	latitude	longitude	depth	sensor h1, h2 + 090	Recording
P58	Wil-731A,HS-1	37.93372	122.41313	--- m	N0°E	6/97-present
P34	Wil-731A,HS-1	37.9358	122.4454	-----		8/97-present

Table 4: San Mateo Bridge Recording sites

i.d.	sensors	latitude	longitude	depth	sensor h1, h2 + 090	Recording
P343	Wil-731A,HS-1	37.786	122.391	298.4 m	N0°E	not recorded

Table 5: Carqueniz Bridge Recording sites

i.d.	sensors	latitude	longitude	depth	sensor h1, h2 + 090	Recording
CRSB	Wil-731A,HS-1	37.786	122.391	38.4 m	N0°E	6/98-present

Table 6: Events Recorded in the Study

Earthquake	Time	Latitude	Longitude	Depth	Magnitude
1996/02/04	23:27:28.74	37.8798	-122.3200	10.89	1.60
1996/03/20	00:31:27.07	37.7768	-122.1915	11.03	2.00
1996/04/12	08:52:28.73	38.1750	-122.4807	12.34	2.40
1996/04/14	13:36:21.37	37.7743	-122.3703	14.51	1.60
1996/04/24	05:21:05.06	37.7657	-122.1458	11.16	2.20
1996/05/14	17:51:08.00	37.9118	-122.2825	6.43	2.10
1996/05/15	04:11:36.96	37.8017	-122.1988	10.50	1.90
1996/05/21	20:50:20.16	37.3593	-121.7227	8.14	4.50
1996/05/30	02:50:45.66	37.8712	-122.2387	11.16	2.00
1996/05/31	08:36:47.55	37.8745	-122.2415	9.51	1.80
1996/07/01	04:33:05.12	37.7148	-122.5447	10.94	3.10
1996/07/04	19:53:00.53	38.3755	-122.6115	8.58	2.70
1996/08/25	23:20:48.27	37.8513	-122.2128	9.33	2.00
1996/10/31	23:09:43.37	37.7553	-122.1667	9.46	2.30
1996/12/24	16:16:54.79	37.7355	-122.5455	6.56	2.20
1996/12/31	05:39:41.80	37.8787	-122.2495	9.85	1.50
1997/02/05	00:25:41.05	38.3647	-122.6513	6.75	3.70
1997/02/14	10:35:31.48	37.7072	-122.1168	7.85	1.60
1997/02/17	16:51:14.89	38.7943	-122.7450	1.04	1.10
1997/02/20	13:43:38.60	37.8415	-122.2280	5.61	1.80
1997/03/11	06:30:16.33	37.7123	-122.5663	5.22	3.50
1997/03/11	06:32:36.58	37.7137	-122.5653	4.96	2.40
1997/03/11	06:33:53.43	37.7137	-122.5663	4.92	3.40
1997/03/11	06:41:33.68	37.7125	-122.5658	4.78	2.30
1997/03/18	13:50:05.62	37.4263	-121.7722	8.20	2.00
1997/03/27	11:30:07.00	38.1483	-121.9372	21.55	3.40

Table 6: Events Recorded in the Study

Earthquake	Time	Latitude	Longitude	Depth	Magnitude
1997/03/27	13:38:08.82	38.1497	-121.9255	21.43	3.20
1997/03/27	15:39:49.01	38.1492	-121.9365	21.65	3.70
1997/03/27	22:47:53.00	38.1500	-121.9333	22.13	3.50
1997/03/28	04:26:31.49	37.3080	-122.0988	5.78	2.50
1997/03/30	06:34:01.38	38.0257	-122.3765	7.32	2.30
1997/04/01	01:36:54.87	38.1492	-121.9335	21.81	3.60
1997/04/03	17:31:22.25	37.8668	-122.2388	10.01	1.90
1997/04/06	07:41:36.05	38.8107	-122.7743	2.76	1.20
1997/04/14	10:29:05.12	38.8430	-122.7910	1.96	1.60
1997/04/22	11:18:08.04	37.4282	-121.7708	10.14	3.30
1997/05/01	00:38:33.72	37.4247	-121.7695	9.02	1.90
1997/05/01	09:45:15.15	37.5083	-121.6778	9.46	2.30
1997/05/02	09:02:20.42	37.5082	-121.6773	9.50	2.30
1997/05/02	11:30:37.62	37.7062	-122.5175	5.20	2.50
1997/05/02	12:31:05.61	37.7070	-122.5163	4.97	3.15
1997/05/20	09:22:32.41	37.5668	-121.8787	9.20	1.30
1997/05/29	10:21:06.83	37.1167	-121.5210	8.06	3.59
1997/05/29	18:28:44.09	37.1190	-121.5230	8.16	3.50
1997/06/19	00:35:29.87	37.7795	-122.5942	3.08	2.50
1997/06/19	04:11:42.66	37.7795	-122.5963	2.96	2.20
1997/06/22	16:26:29.38	37.5782	-121.9513	9.63	1.70
1997/06/25	01:11:34.86	37.8477	-122.2308	4.75	1.10
1997/06/25	03:13:59.46	37.8547	-122.2253	8.09	1.60
1997/07/04	02:59:17.16	37.3053	-122.3543	6.04	2.20
1997/07/09	16:14:47.66	37.9337	-122.0262	11.80	2.90
1997/07/11	08:31:27.02	37.6440	-122.0452	2.08	1.60
1997/07/14	06:11:11.70	37.1722	-122.3348	14.01	3.76

Table 6: Events Recorded in the Study

Earthquake	Time	Latitude	Longitude	Depth	Magnitude
1997/07/17	20:16:00.69	38.8090	-122.8147	3.87	1.30
1997/07/30	11:30:38.93	37.5715	-121.6672	7.68	3.16
1997/08/12	22:01:59.62	37.5872	-121.9707	6.60	2.00
1997/08/14	08:53:35.67	37.7370	-122.5477	1.84	3.02
1997/08/17	18:41:54.17	37.8682	-122.2390	10.07	1.30
1997/08/23	14:26:18.95	37.3732	-121.7343	6.40	2.40
1997/08/23	14:27:02.59	37.3733	-121.7340	6.34	2.00
1997/08/27	20:29:17.27	38.8448	-122.7990	1.42	1.00
1997/08/31	00:24:13.99	37.7360	-122.0900	9.42	2.92
1997/08/31	17:18:45.07	38.8303	-122.8630	0.80	1.10
1997/09/03	19:00:30.83	38.8007	-122.7728	1.80	1.30
1997/09/08	00:10:38.00	37.8595	-122.2328	9.60	1.40
1997/09/12	21:19:18.84	37.7923	-122.6233	5.20	2.00
1997/09/18	04:25:53.59	37.3708	-122.1452	6.06	2.50
1997/09/23	09:52:20.92	37.1792	-122.0695	16.09	2.10
1997/09/24	04:41:33.71	37.9675	-122.3390	6.98	2.50
1997/09/26	19:58:02.47	37.2863	-121.6640	6.96	3.19
1997/10/19	05:23:54.17	37.4505	-121.7720	7.94	1.20
1997/10/27	00:29:13.68	37.6815	-121.8393	9.65	2.50
1997/10/27	14:30:50.65	37.7265	-122.5473	10.15	2.90
1997/11/15	15:51:59.78	38.8257	-122.8318	1.36	1.60
1997/11/19	21:05:17.94	37.6192	-122.0158	4.76	3.23
1997/11/29	00:31:12.53	38.7748	-122.7520	1.89	1.20
1997/12/13	11:51:16.16	37.2828	-122.0525	5.68	2.97
1997/12/23	15:11:33.73	37.5337	-121.8008	8.37	1.50
1998/01/17	10:00:12.93	37.8108	-122.1928	4.49	2.40
1998/02/05	10:00:37.13	38.7812	-122.7477	4.31	1.10

Table 6: Events Recorded in the Study

Earthquake	Time	Latitude	Longitude	Depth	Magnitude
1998/02/05	12:49:15.58	38.8555	-122.8638	7.28	1.30
1998/02/05	17:42:20.63	38.7915	-122.7762	2.37	1.70
1998/02/06	14:28:24.04	38.8035	-122.8060	2.31	1.40
1998/02/06	17:17:21.10	38.7810	-122.7250	2.47	2.60
1998/02/07	17:14:50.24	38.8267	-122.8080	4.00	1.60
1998/02/07	20:18:24.25	37.1395	-121.5558	0.04	1.30
1998/02/08	18:50:48.90	37.9643	-122.0393	12.90	2.40
1998/03/14	10:52:27.96	37.3777	-122.2660	9.56	2.80
1998/03/31	11:44:09.90	38.7748	-122.7452	4.06	2.70
1998/04/03	19:37:45.14	38.8898	-123.0323	2.01	1.60
1998/04/10	04:07:49.46	37.8670	-122.2427	10.34	1.50
1998/05/06	11:34:37.96	38.8055	-122.7363	2.75	1.40
1998/05/08	08:06:30.49	38.7985	-122.7760	4.81	1.60
1998/05/09	04:27:07.86	37.7557	-122.5663	7.23	2.40
1998/05/09	10:41:24.35	38.7823	-122.7627	2.11	1.30
1998/05/11	08:45:17.54	38.8162	-122.8112	3.59	1.30
1998/05/13	10:15:19.21	37.5627	-122.3747	5.45	1.10
1998/06/09	02:26:43.61	37.9127	-122.2852	5.81	2.50

Table 7: Bay Bridge Site Recordings

Earthquake	BBW2	BBW5	YBA	BE02	BE07	BE17	BE23	SFA
9602042327						XXXX		
9603200031					XXXX			
9604120852					XXXX			
9604141336					XXXX			
9604240521					XXXX			

Table 7: Bay Bridge Site Recordings

Earthquake	BBW2	BBW5	YBA	BE02	BE07	BE17	BE23	SFA
9605141751					XXXX			
9605150411					XXXX			
9605212050	XXXX							
9605300250					XXXX			
9605310836					XXXX			
9607010433				XXXX	XXXX			
9607041952				XXXX				
9608252320				XXXX				
9610312309						XXXX		
9612241616						XXXX		
9612310539						XXXX		
9702050025	XXXX				XXXX			
9702141035					XXXX			
9702171651					XXXX			
9702201343					XXXX			
9703110630	XXXX	XXXX			XXXX			
9703110633	XXXX	XXXX						
9703280426					XXXX			
9703300634					XXXX			
9704031731					XXXX			
9705021130	XXXX							
9705021231	XXXX							
9705291021		XXXX						
9706190035						XXXX		
9706190411						XXXX		
9706250111						XXXX		
9706250313						XXXX		

Table 7: Bay Bridge Site Recordings

Earthquake	BBW2	BBW5	YBA	BE02	BE07	BE17	BE23	SFA
9707091614				XXXX		XXXX		
9707140611					XXXX			
9707171946				XXXX				
9708140853		XXXX		XXXX		XXXX		
9708171841						XXXX		
9708272029					XXXX			
9708310024		XXXX			XXXX	XXXX		
9708311718					XXXX			
9709031900					XXXX			
9709080010						XXXX		
9709122119						XXXX		
9709240441		XXXX						
9710190523					XXXX			
9710271430	XXXX	XXXX		XXXX				
9711151551					XXXX			
9711192105		XXXX		XXXX				
9711290031						XXXX		
9712131151	XXXX				XXXX			
9712231511						XXXX		
9801171000	XXXX	XXXX			XXXX	XXXX		
9802051000					XXXX			
9802051249					XXXX			
9802051742					XXXX			
9802061428						XXXX		
9802061717					XXXX			
9802071714					XXXX			
9802072018						XXXX		

Table 7: Bay Bridge Site Recordings

Earthquake	BBW2	BBW5	YBA	BE02	BE07	BE17	BE23	SFA
9802081850					XXXX	XXXX		
9803141052	XXXX							
9803311144					XXXX			
9804031937					XXXX			
9804100407						XXXX		
9805061134								XXXX
9805080806								XXXX
9805090427	XXXX							
9805091041								XXXX
9805110845								XXXX
9805131015								XXXX
9806090226	XXXX				XXXX			

Table 8: Dumbarton Bridge Site Recordings

Earthquake	DB01	DB27	DB44
9703110630		XXXXXXXXXX	XXXXXXXXXX
9703110632		XXXXXXXXXX	XXXXXXXXXX
9703110633		XXXXXXXXXX	XXXXXXXXXX
9703110641		XXXXXXXXXX	XXXXXXXXXX
9703181350		XXXXXXXXXX	
9703271130		XXXXXXXXXX	XXXXXXXXXX
9703271338		XXXXXXXXXX	XXXXXXXXXX
9703271539		XXXXXXXXXX	XXXXXXXXXX
9703272247			XXXXXXXXXX
9703280426		XXXXXXXXXX	XXXXXXXXXX
9704010136		XXXXXXXXXX	XXXXXXXXXX

Table 8: Dumbarton Bridge Site Recordings

Earthquake	DB01	DB27	DB44
9704060741	XXXXXXXXXX		
9704141029	XXXXXXXXXX		
9704221118		XXXXXXXXXX	XXXXXXXXXX
9705010038		XXXXXXXXXX	
9705010945			XXXXXXXXXX
9705020902		XXXXXXXXXX	
9705021130		XXXXXXXXXX	
9705021231		XXXXXXXXXX	
9705200922		XXXXXXXXXX	
9705291021		XXXXXXXXXX	
9705291828		XXXXXXXXXX	
9706221626		XXXXXXXXXX	
9707040259		XXXXXXXXXX	
9707091614		XXXXXXXXXX	
9707110831		XXXXXXXXXX	
9707140611		XXXXXXXXXX	
9707301130		XXXXXXXXXX	
9708122201		XXXXXXXXXX	
9708140853		XXXXXXXXXX	
9708231426		XXXXXXXXXX	
9708310024		XXXXXXXXXX	
9709180425		XXXXXXXXXX	
9709230952		XXXXXXXXXX	
9709261958		XXXXXXXXXX	
9710270029		XXXXXXXXXX	
9710271430		XXXXXXXXXX	
9711192105		XXXXXXXXXX	

San Francisco Bay Bridges

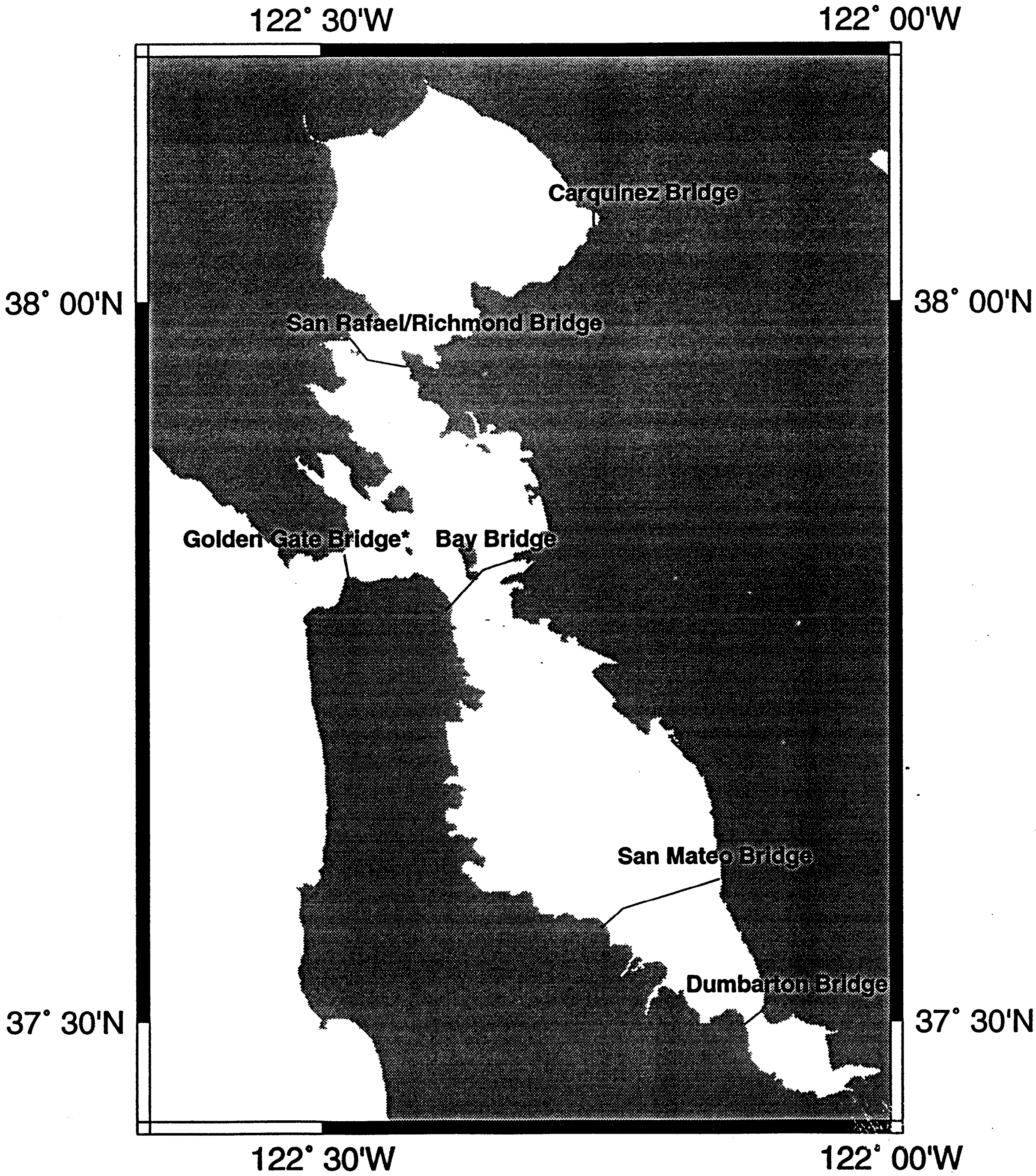


Figure 1: Map of the San Francisco Bay. (*Bridge not used in the bridge network study)

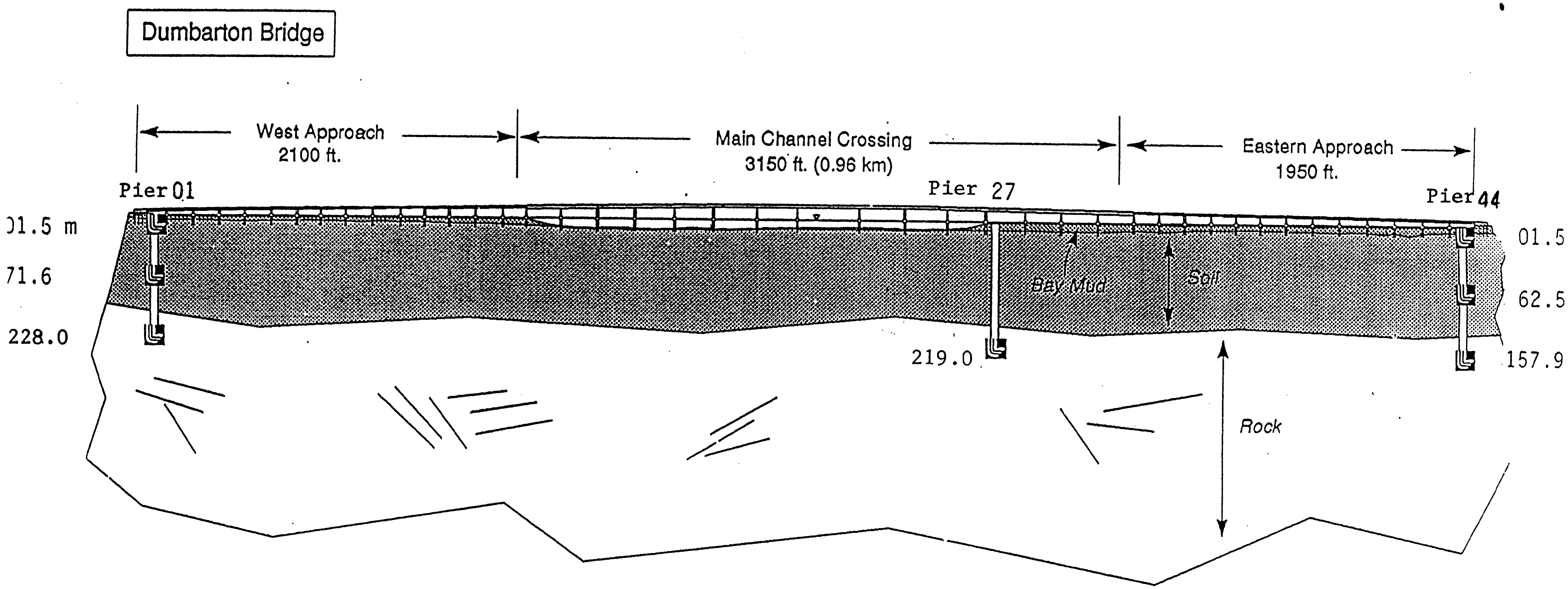


Figure 2: Location of the LLNL seismic instrumentation along the Dumbarton Bridge.

1

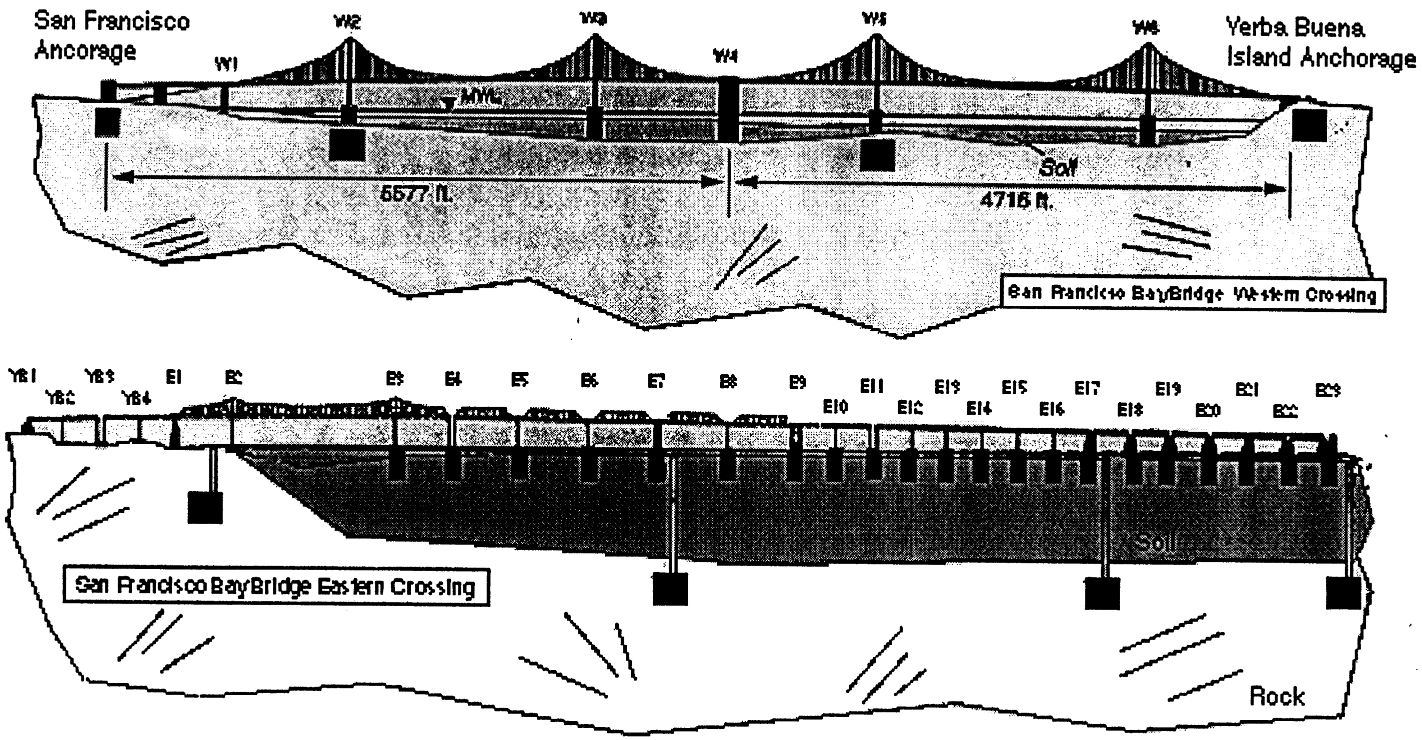


Figure 3: Location of LLNL/UC Berkeley seismic instrumentation along the San Francisco- Oakland Bay Bridge.

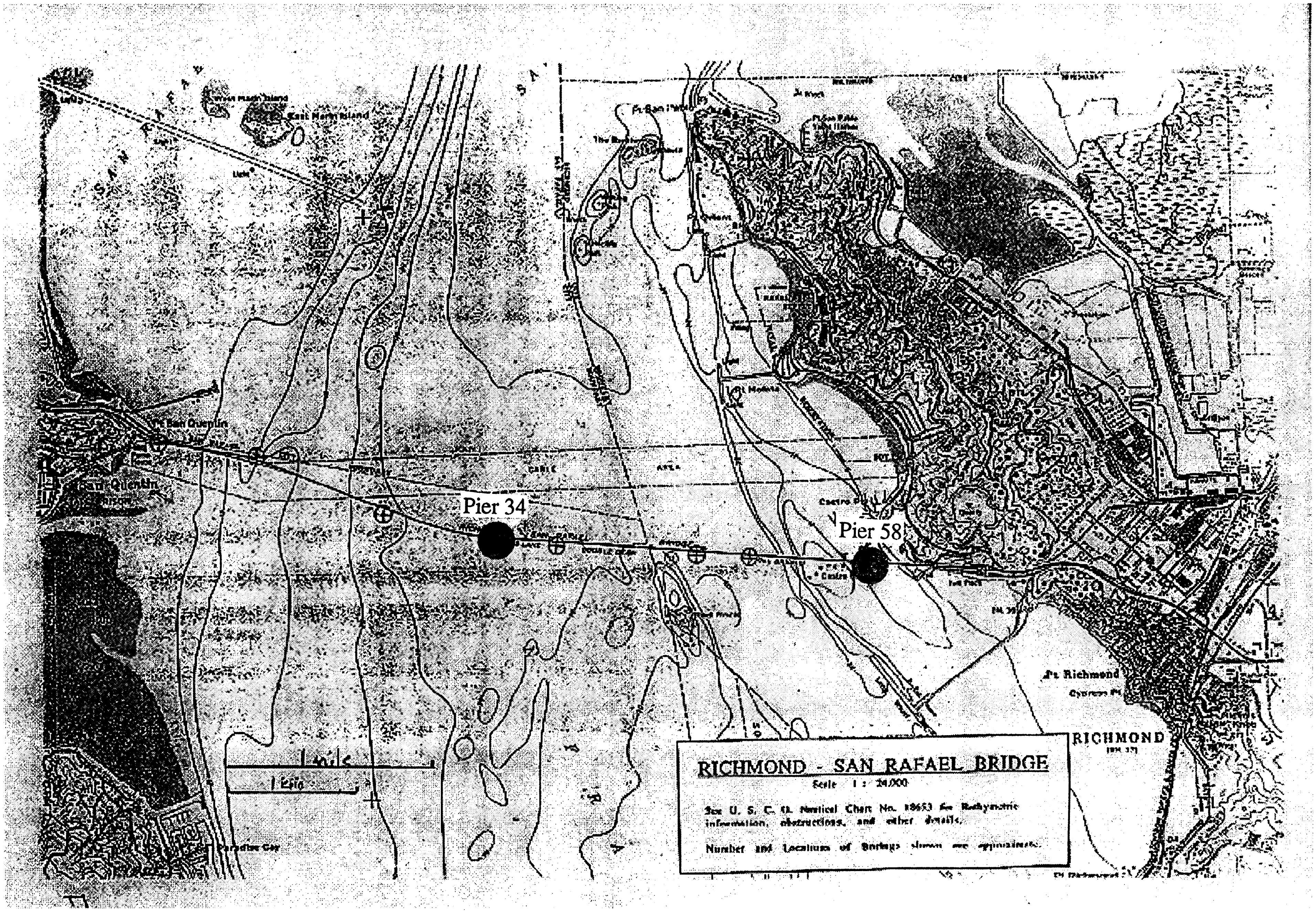


Figure 4: Location of seismic instrumentation along the Richmond- San Rafael Bridge.

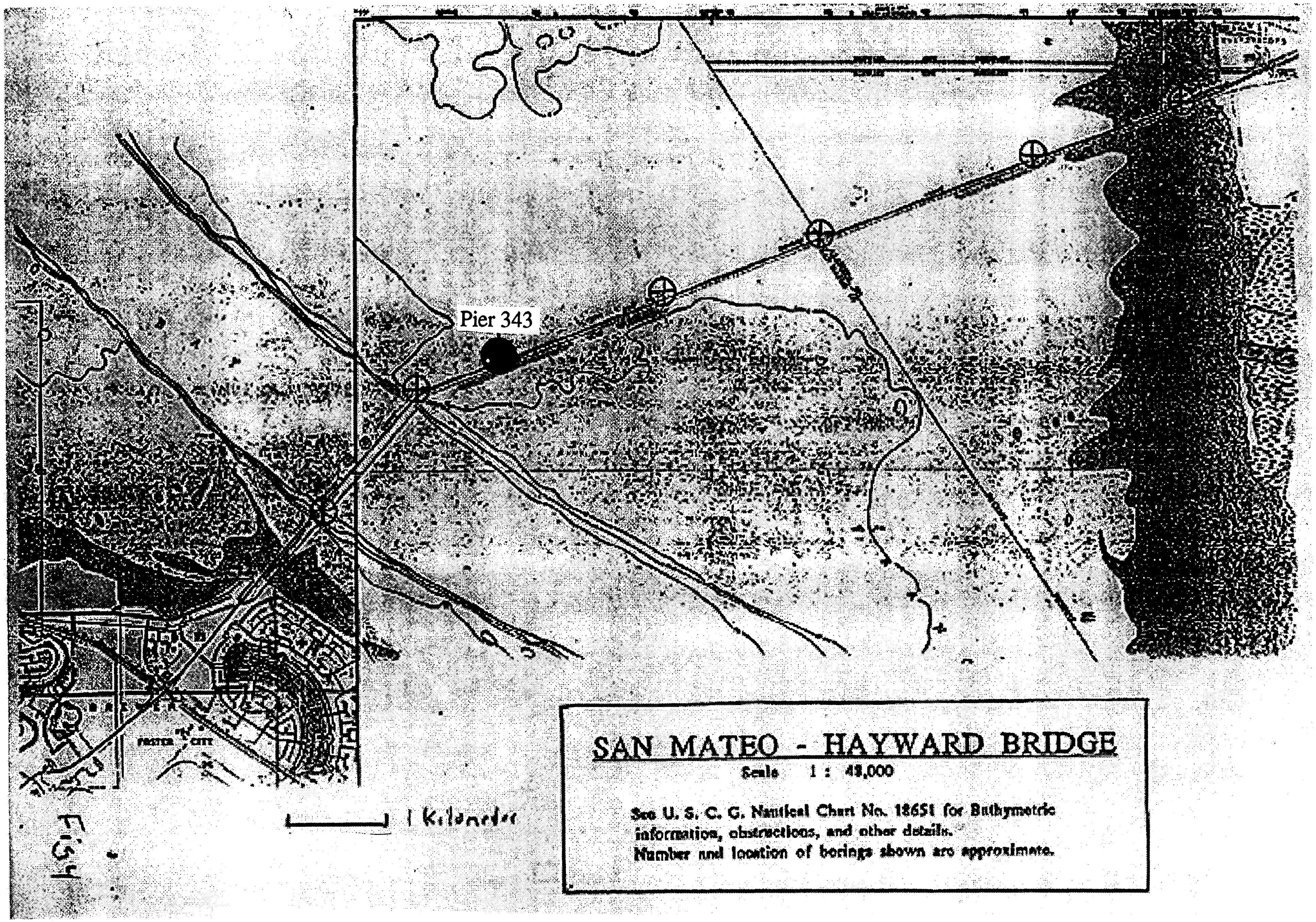


Figure 5: Location of seismic instrumentation along the San Mateo- Hayward Bridge.

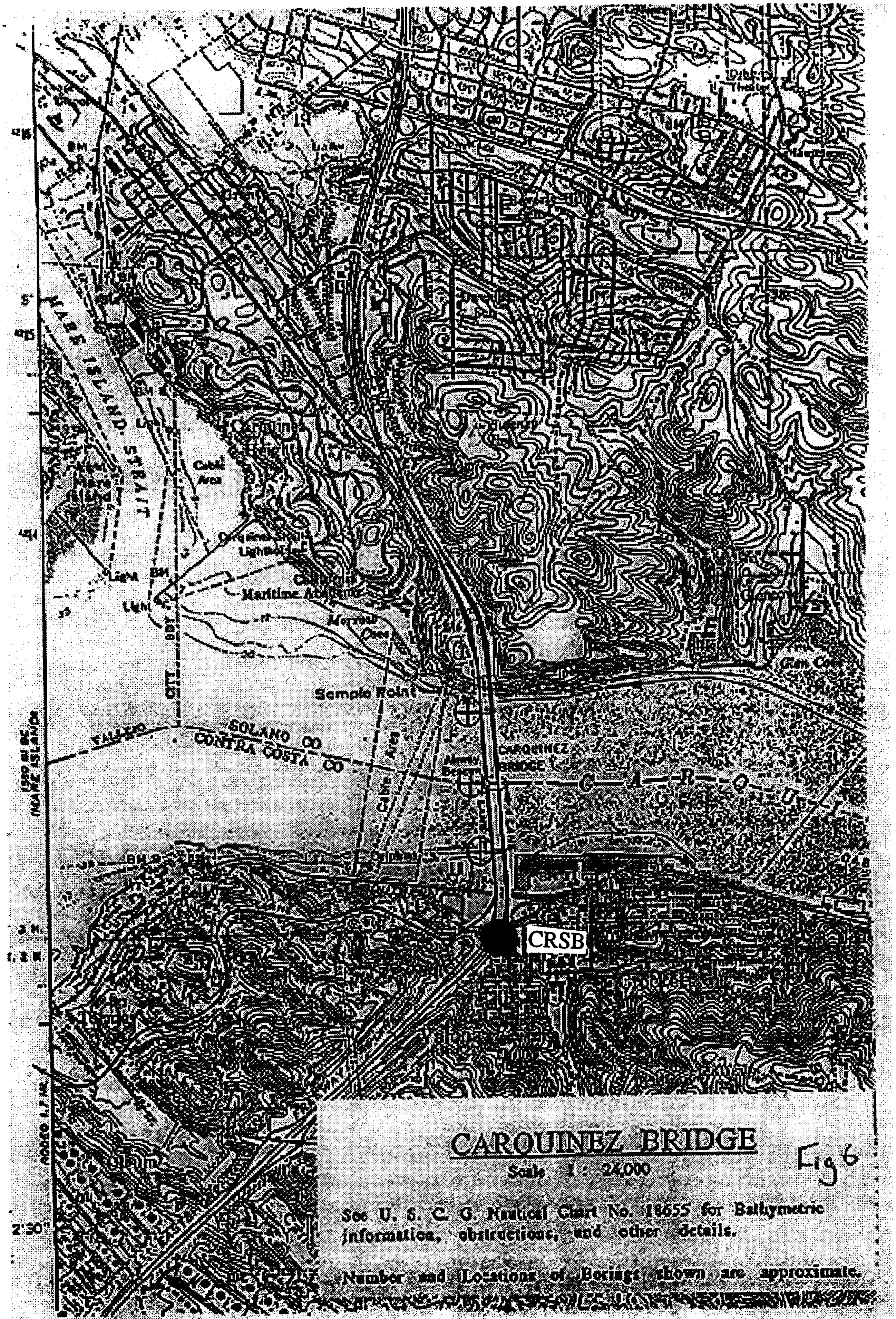


Figure 6: Location of seismic instrumentation along the Carqueniz Bridge.

Bay Bridge Recordings

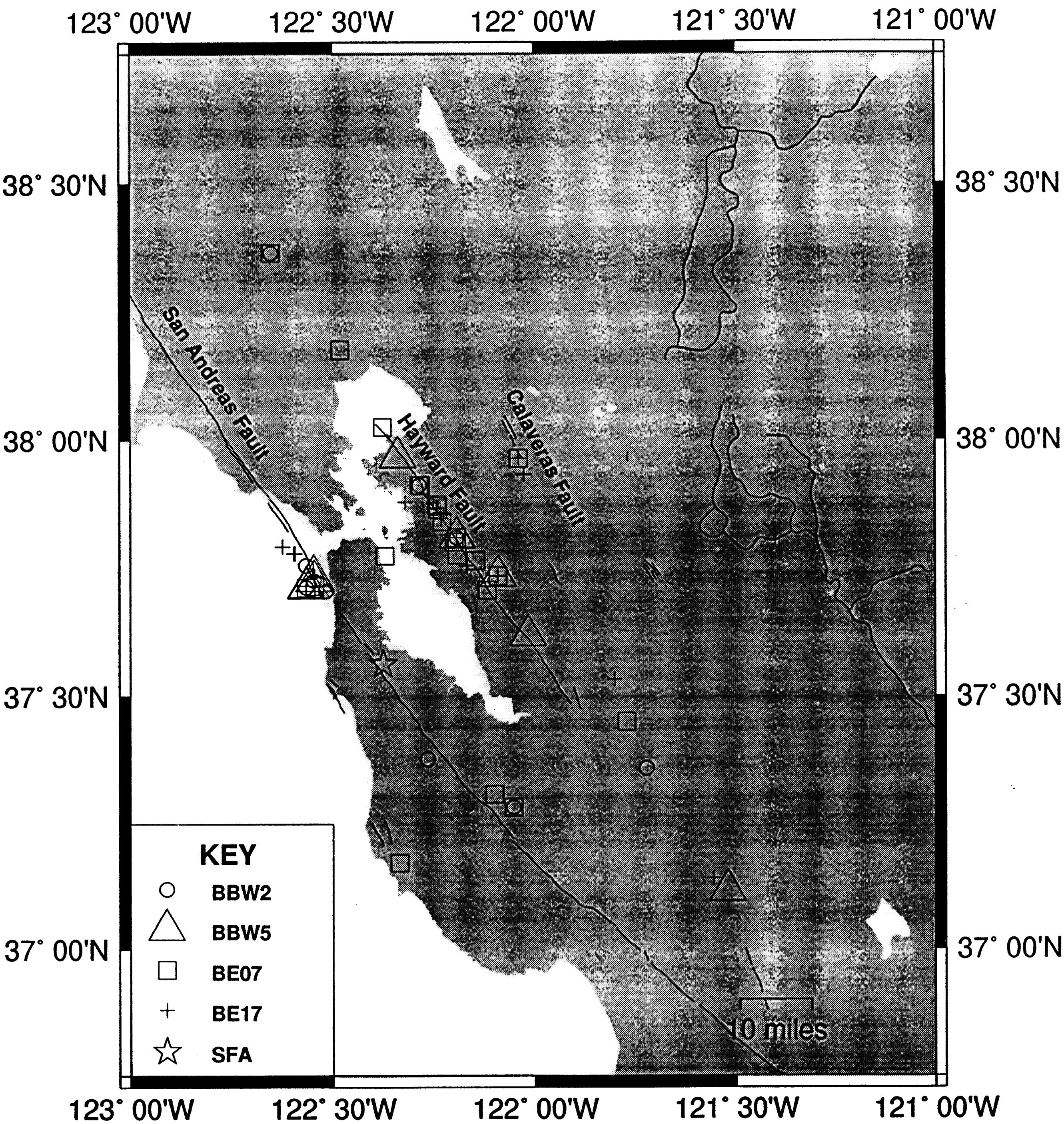


Figure 7: Plot of earthquakes recorded by the Bay Bridge recorders.

Dumbarton Bridge Recordings

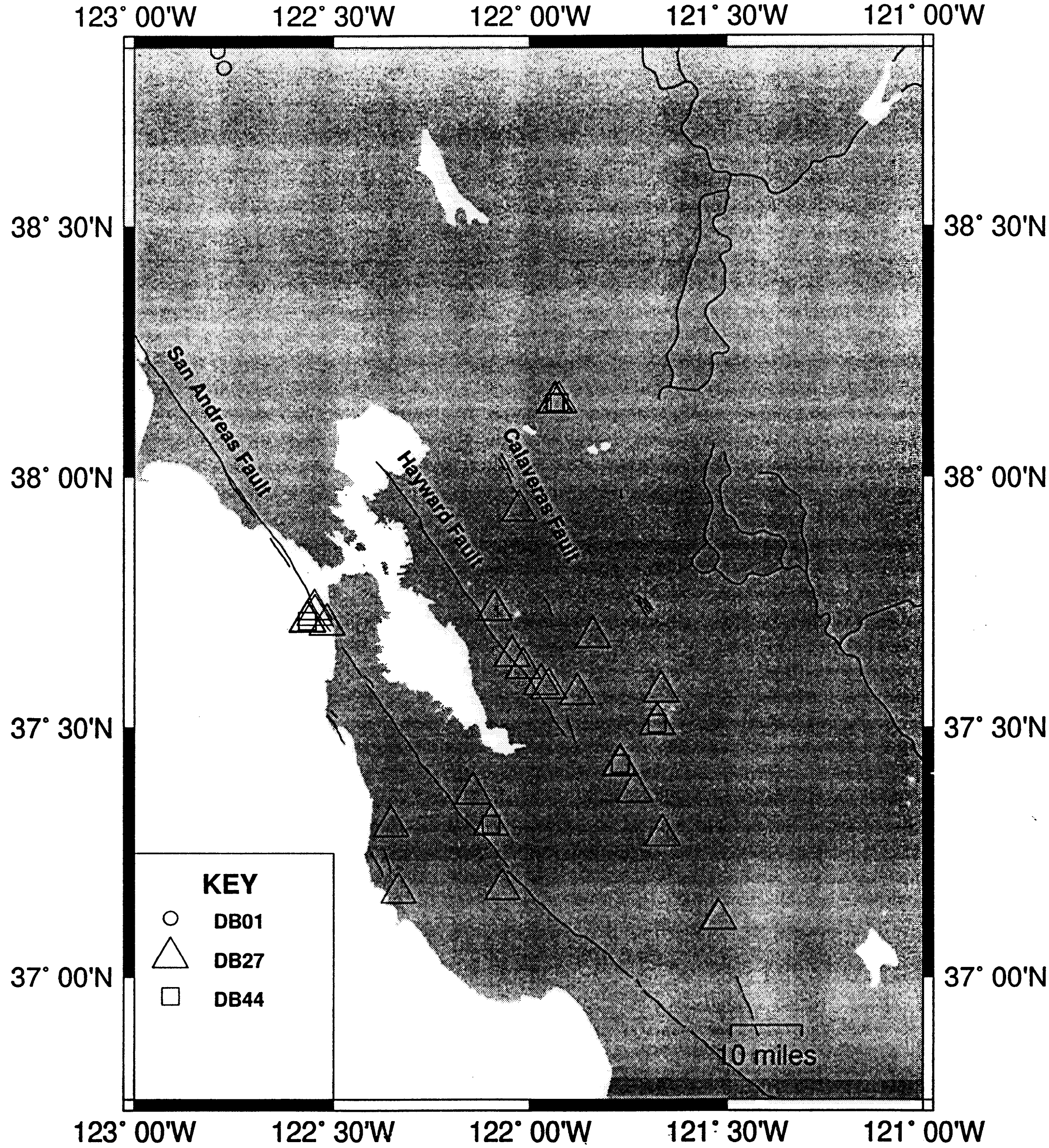


Figure 8: Plot of earthquakes recorded by the Dumbarton Bridge recorders.

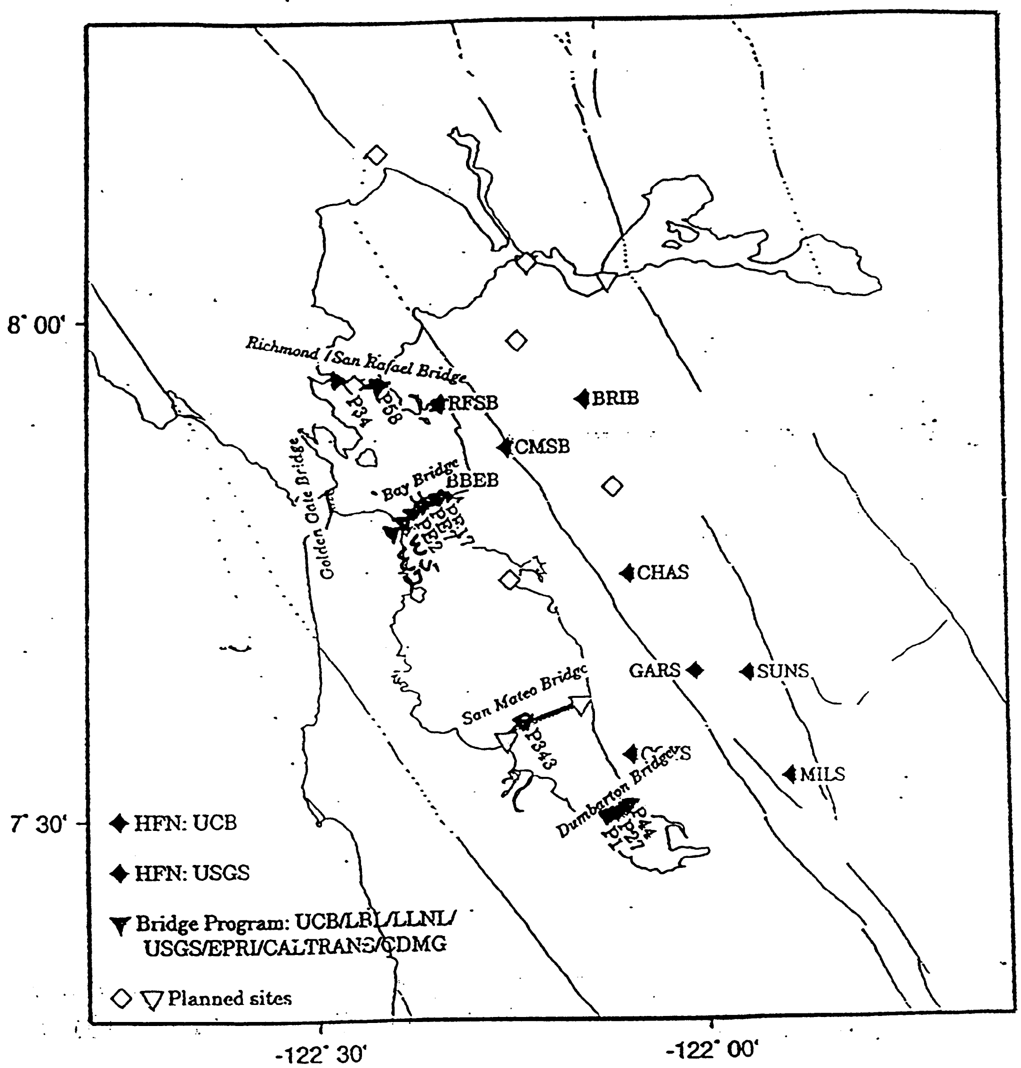


Figure 9: Locations of Bay Area Borehole Network. Instruments are placed 100' into bedrock.

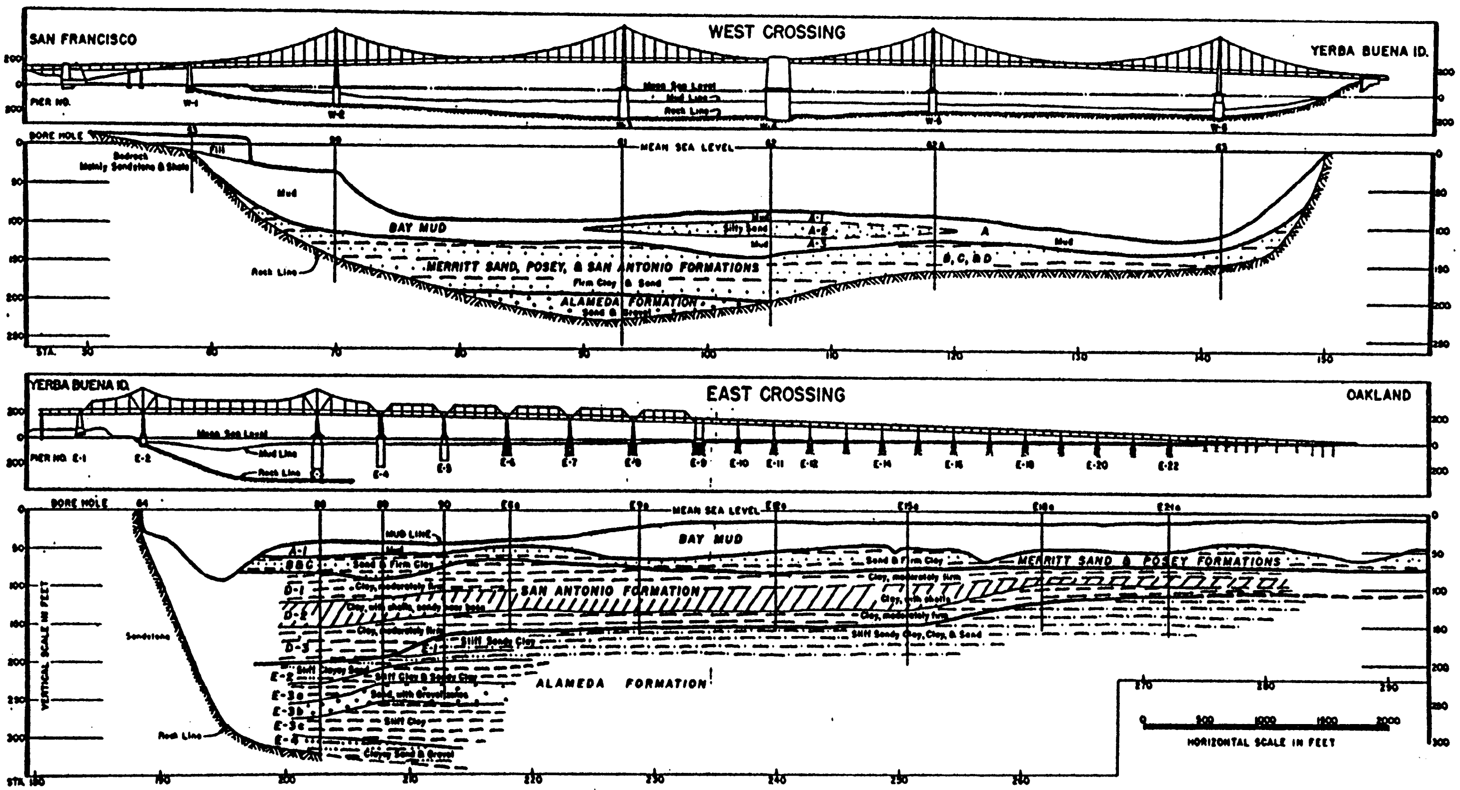


Figure 10: Subsurface geology beneath the San Francisco- Oakland Bay Bridge as inferred by Trask and Rolston (1951) and later updated by Rogers and Figures, 1991, *Engineering Geologic Site Characterization of the Greater Oakland- Alameda Area, Alameda and San Francisco Counties, California* : NSF Report, p. 46.

Depth to Bedrock

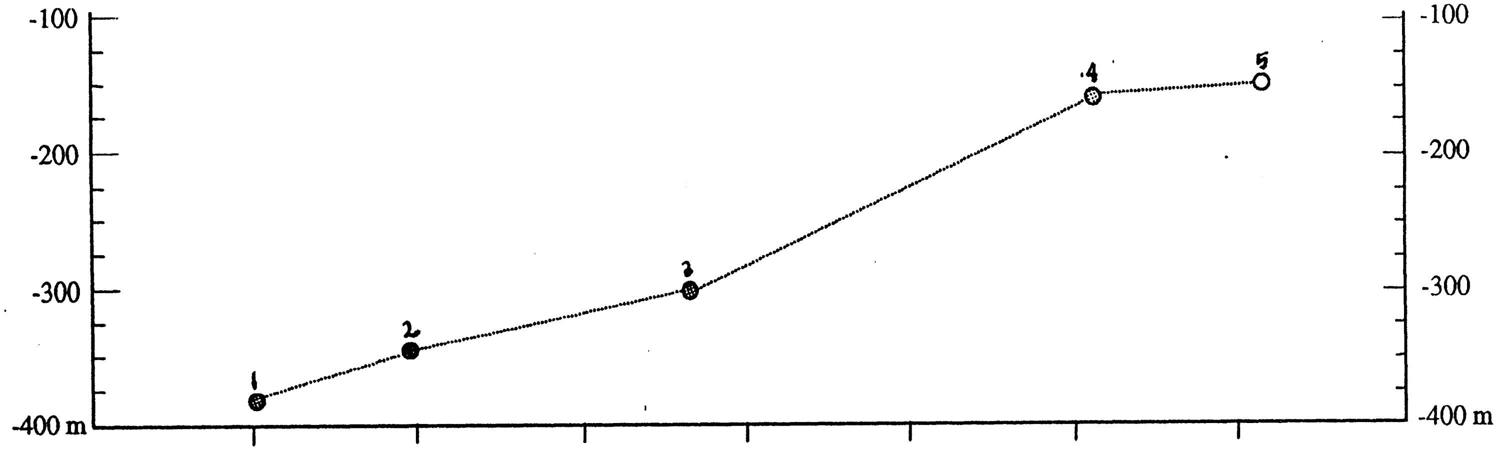
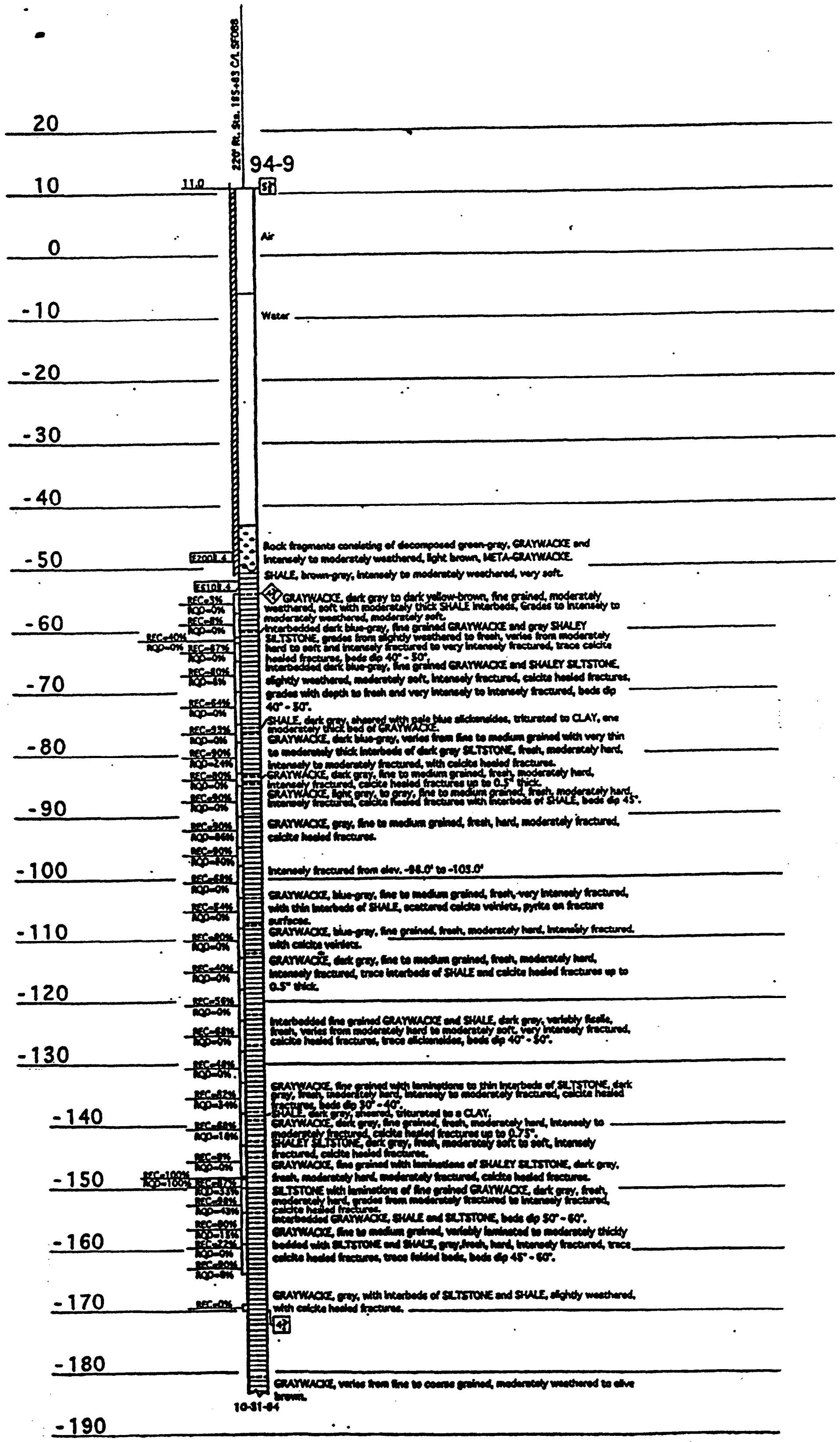


Figure 11: Depth to bedrock at lowest elevation under each bridge marking the bottom of the Alameda formation.

Golden Gate Bridge	1	Carquinez Bridge	4
San Francisco-Oakland Bay Bridge	2	Benica-Martinez Bridge	5
Richmond-San Rafael Bridge	3	1:10,000	



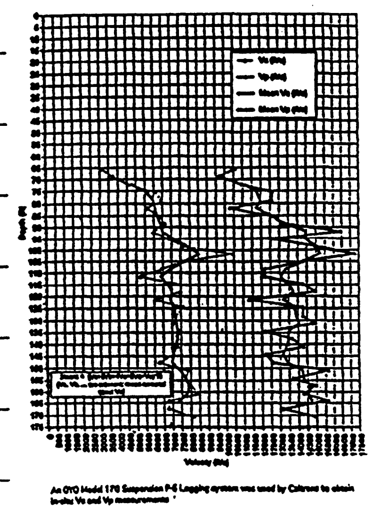


Figure 12: Caltrans borehole log for 94-9, between Pier E-1 and E-2, on the Bay Bridge.

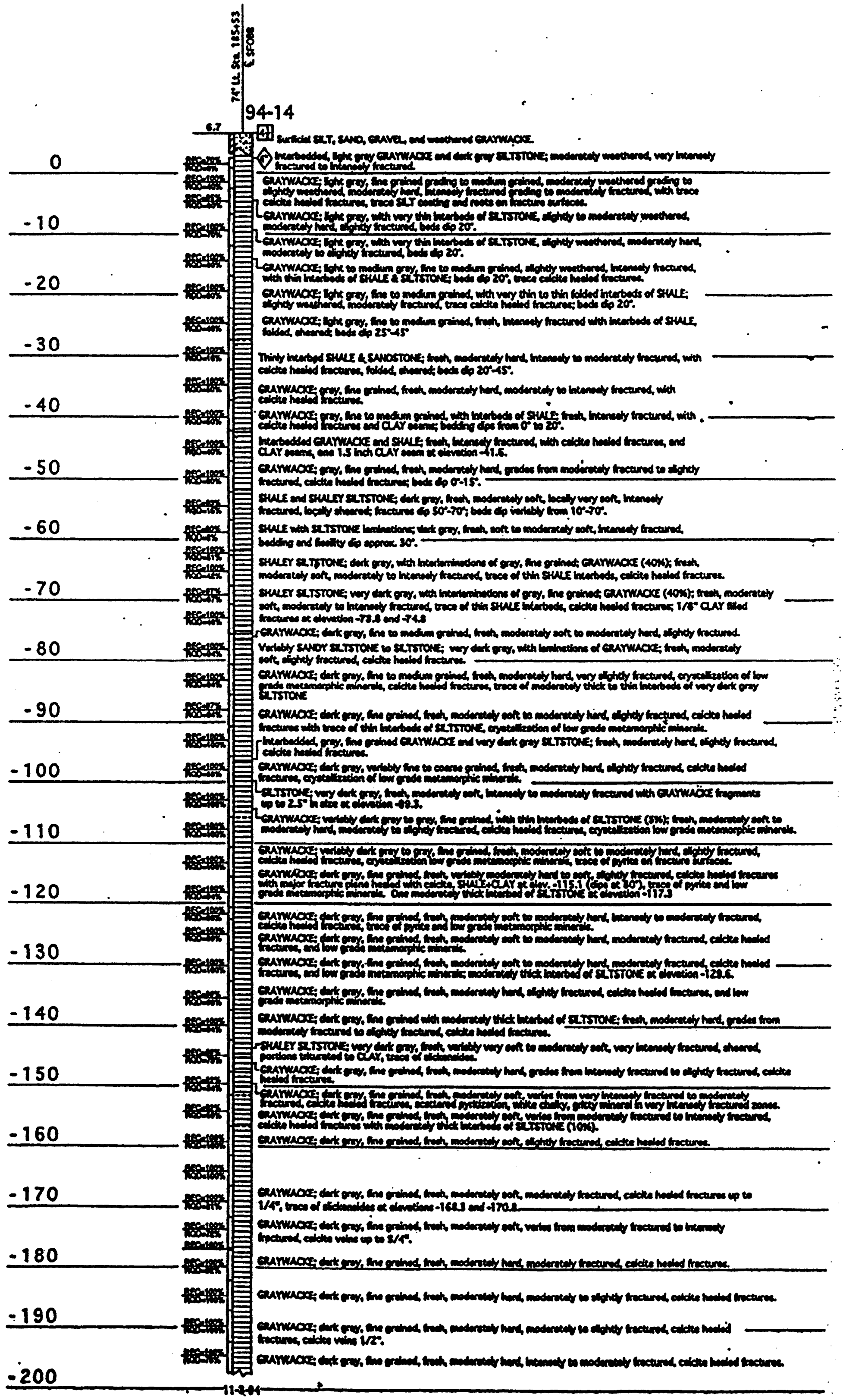


Figure 13: Caltrans borehole log for 94-14, between pier E-1 and E-2, on the Bay Bridge.

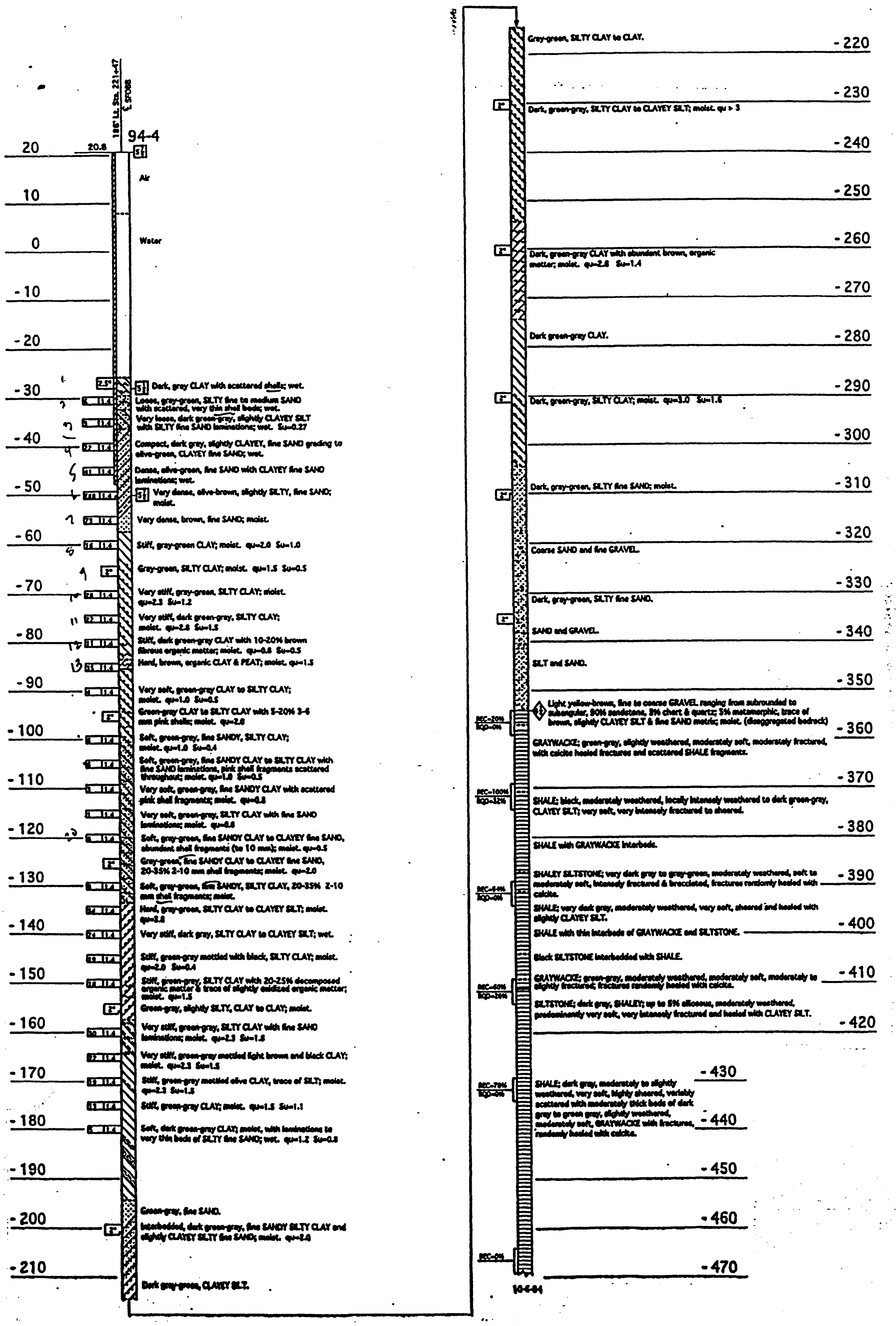


Figure 14: Caltrans borehole for 94-4, pier E-7, on the Bay Bridge.

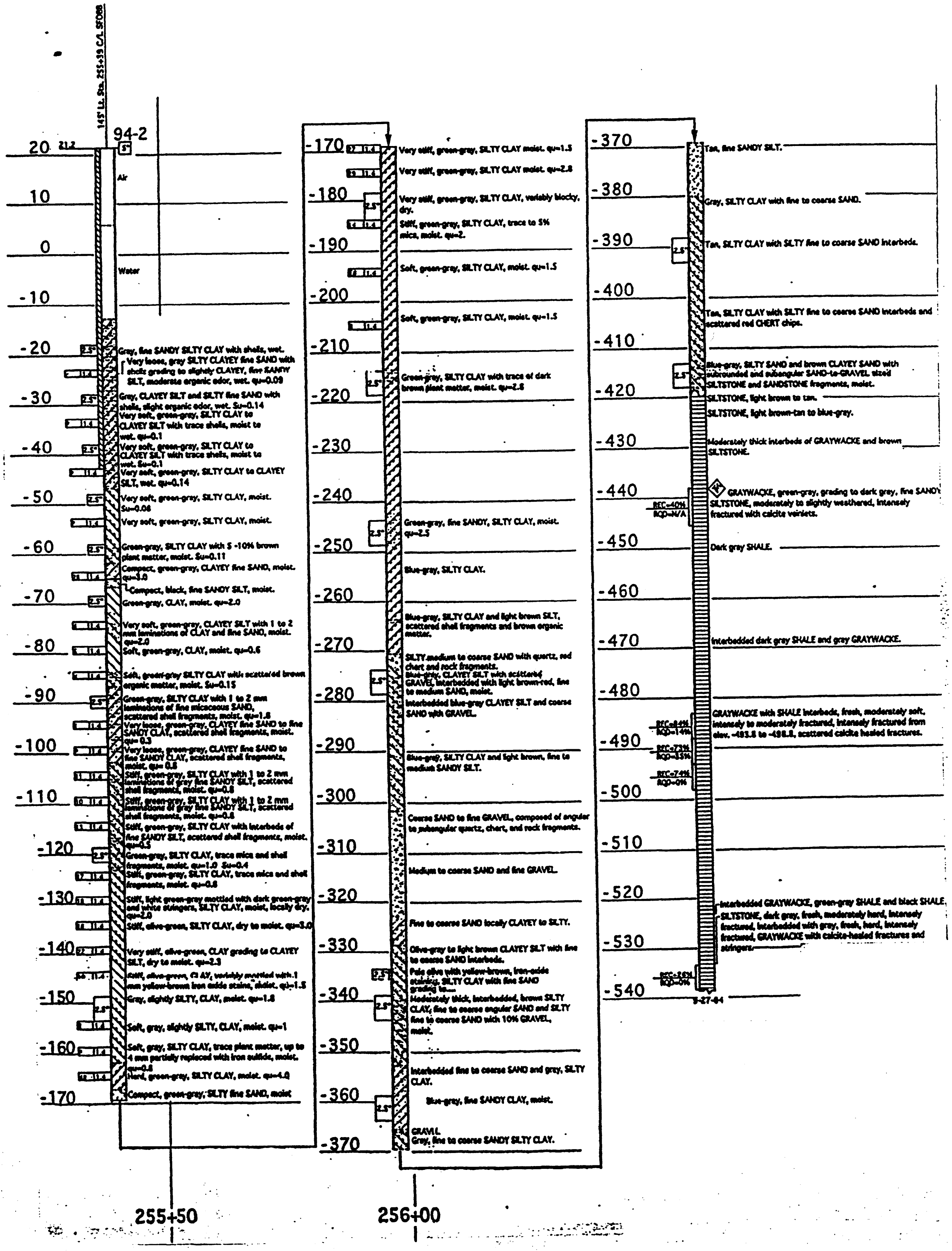
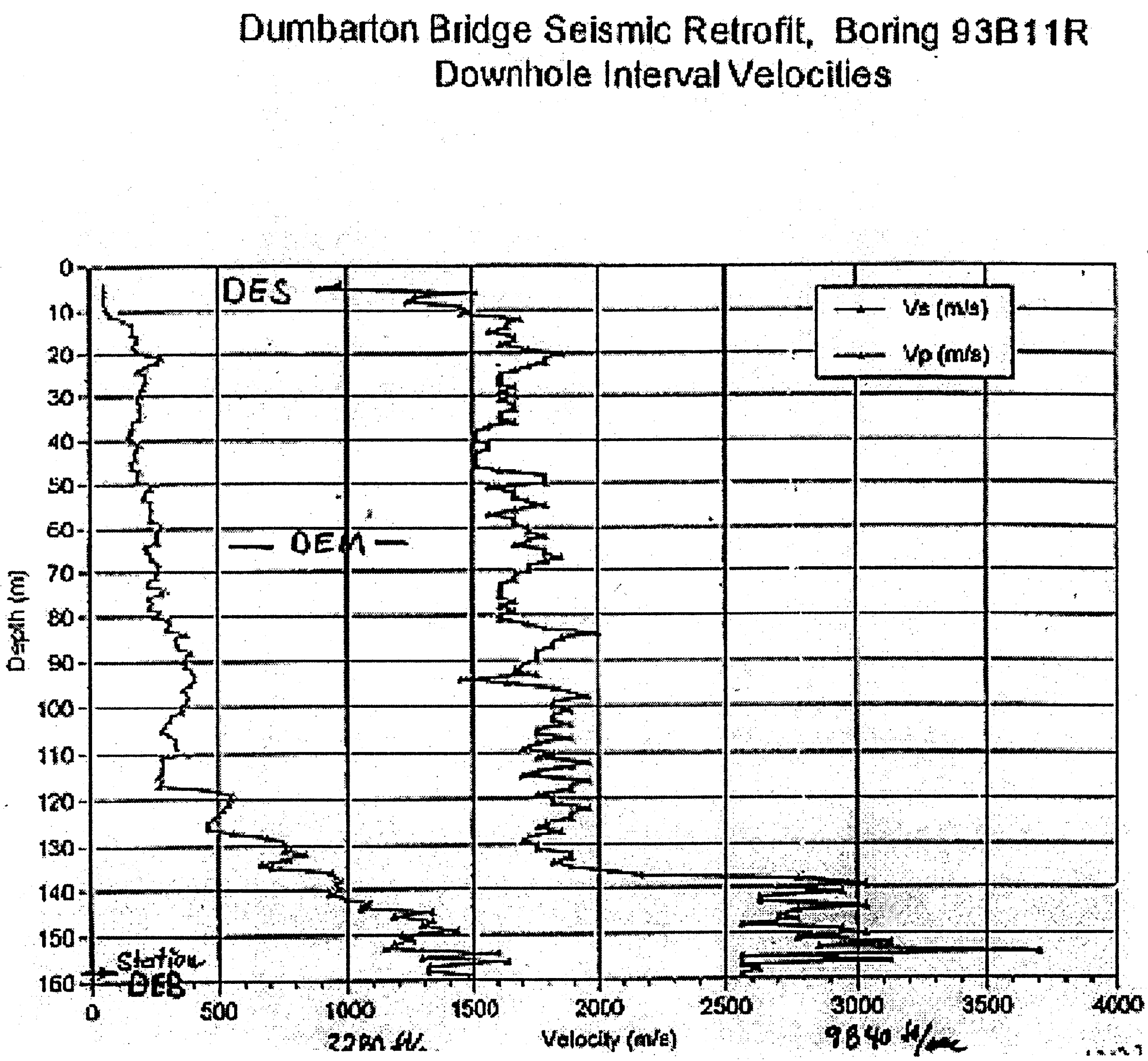


Figure 15: Caltrans borehole log for 94-2, Pier E-17, on the Bay Bridge.



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x 3

Figure 16: Velocity profile for deep hole at the west end, pile 1, of the Dumbarton Bridge.

Fig 13

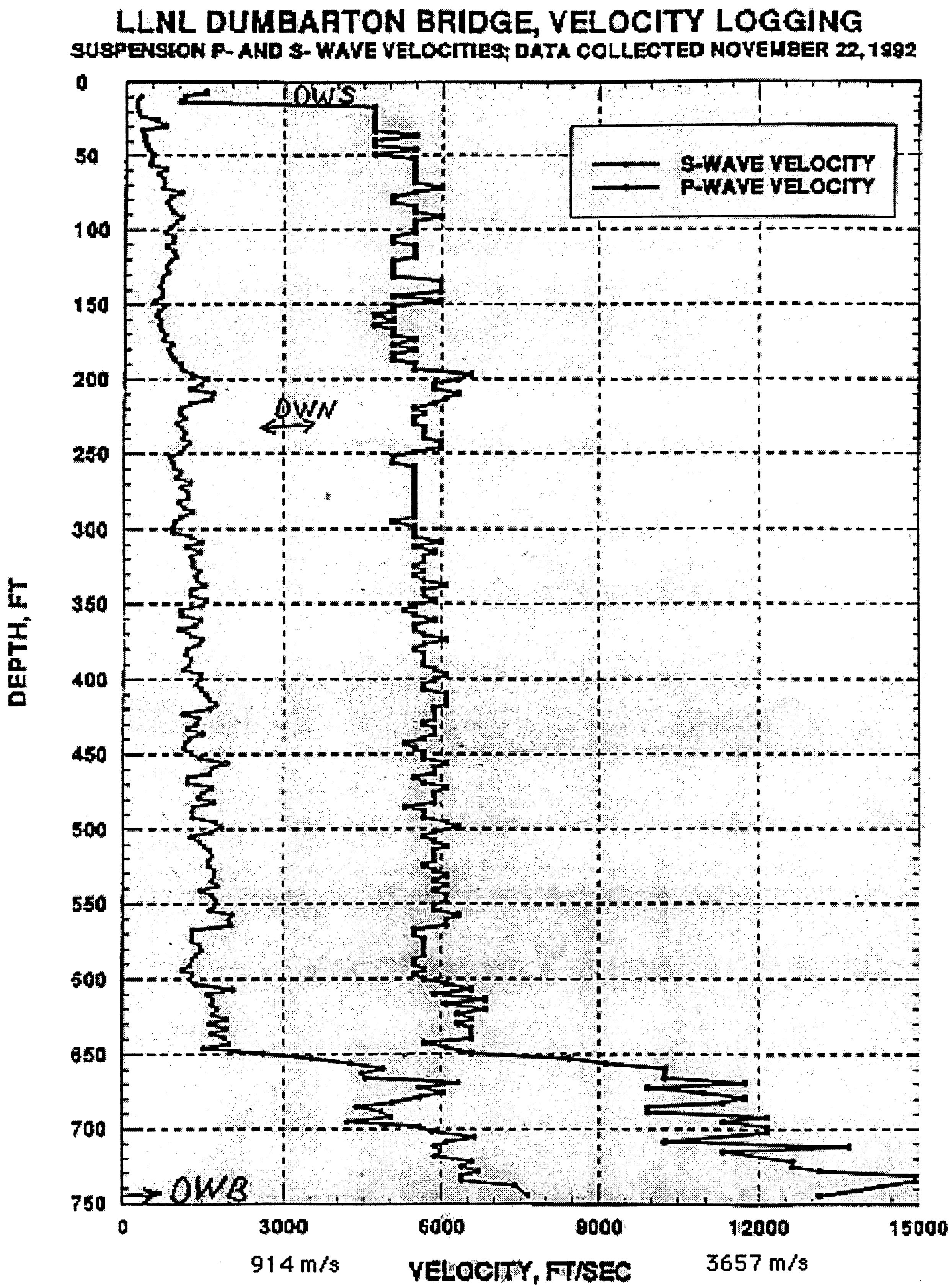


Figure 17: Velocity profile for deep hole at fishing pier, pile 27, of the Dumbarton Bridge.

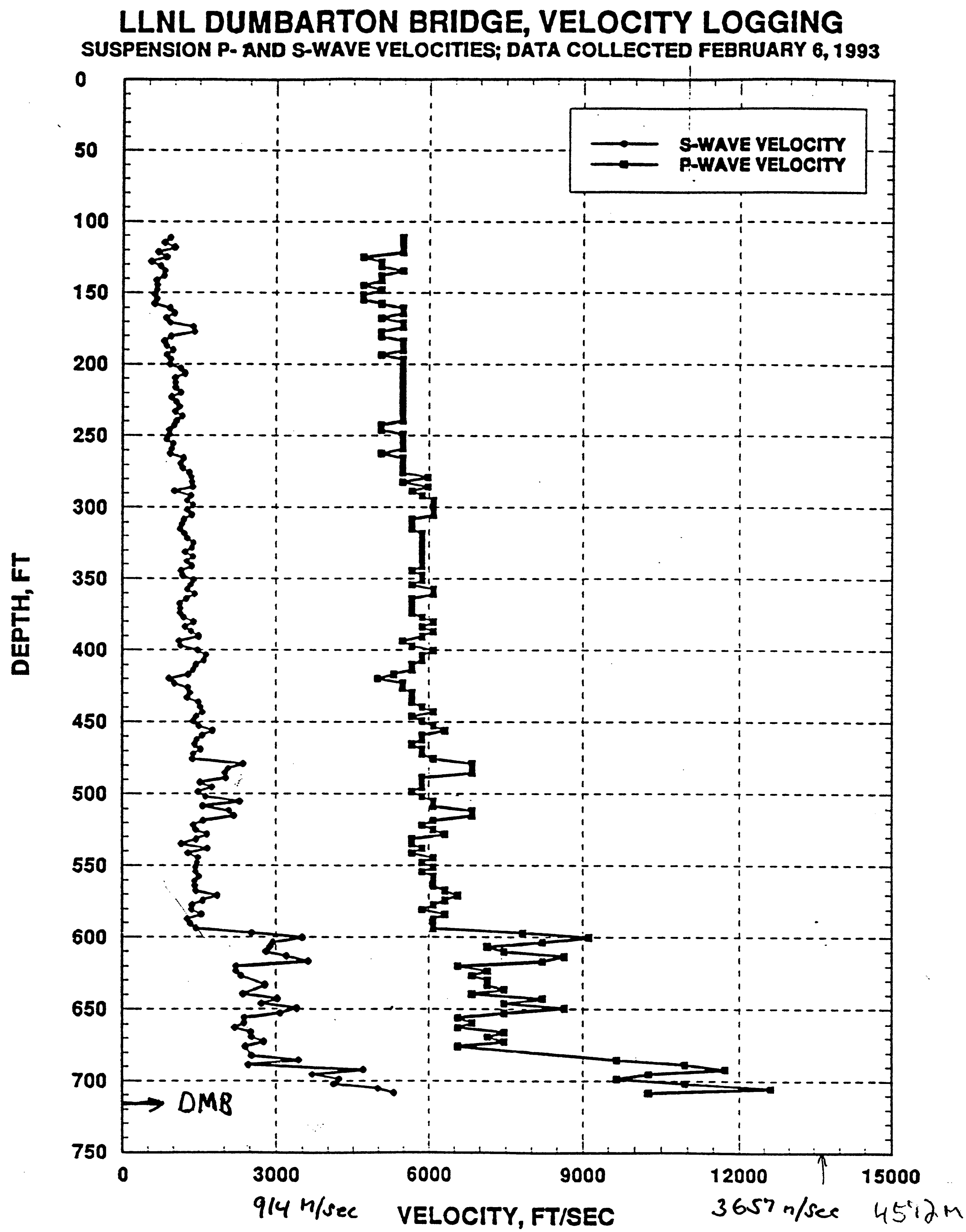
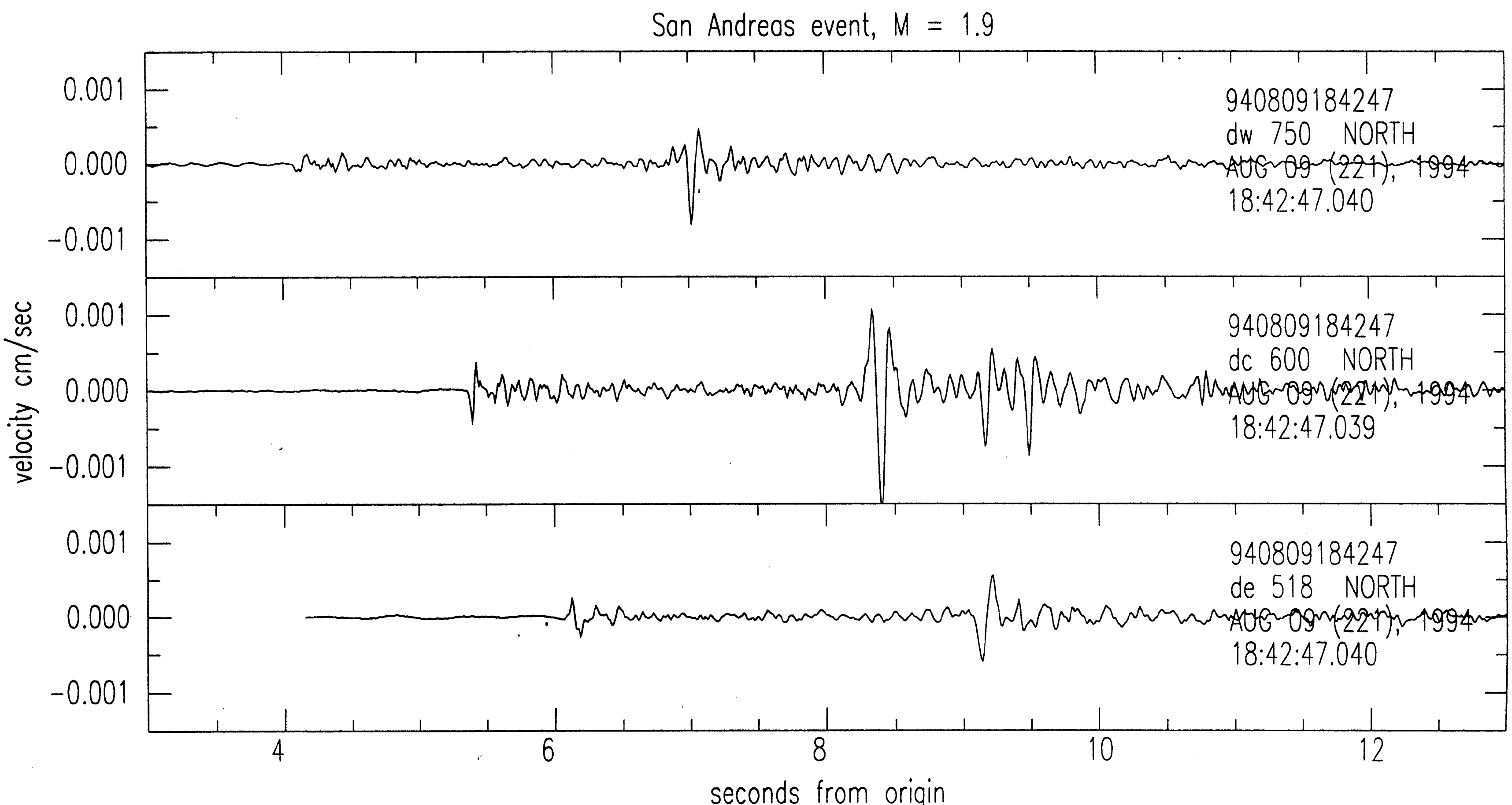


Figure 18: Velocity profile for deep hole on the east end, pile 44, of the Dumbarton Bridge.

Figure 19: Recordings of acceleration at each of the deep bore sensors along the Dumbarton Bridge (north component only) from a M= 1.9 earthquake located 19 km to the west, on the San Andreas fault.



Top and Bottom Borehole Recordings

- linear response amplification
- M=6.5 event at 430 Km

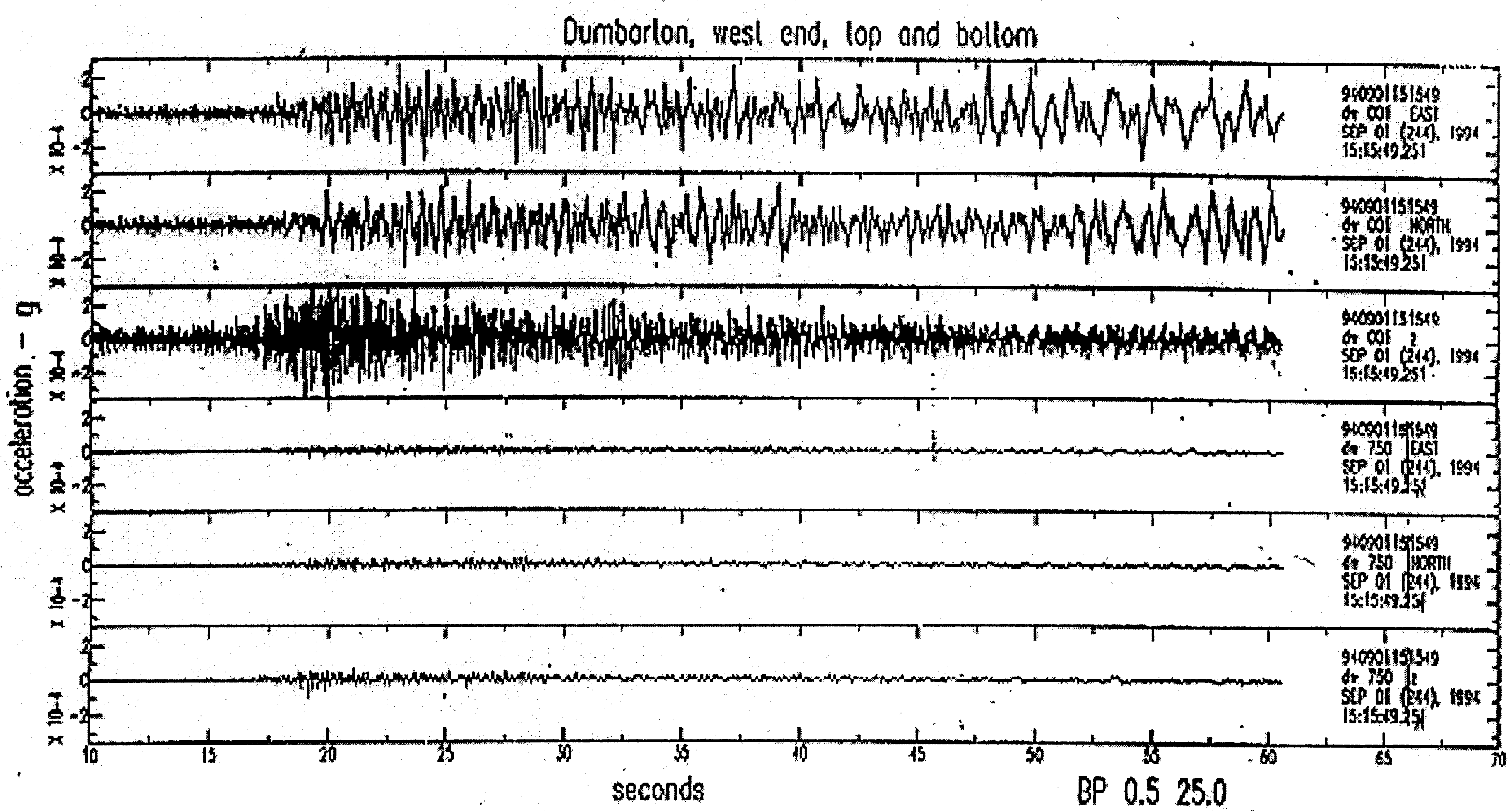


Figure 20: Accelerograms from the top and bottom sensor pairs for a M= 6.5 located 490 km distant, near the Mendocino triple junction.

Top, Middle and Bottom Borehole Amplification

- Fourier amplitude spectra
- rock is highly competent graywacke

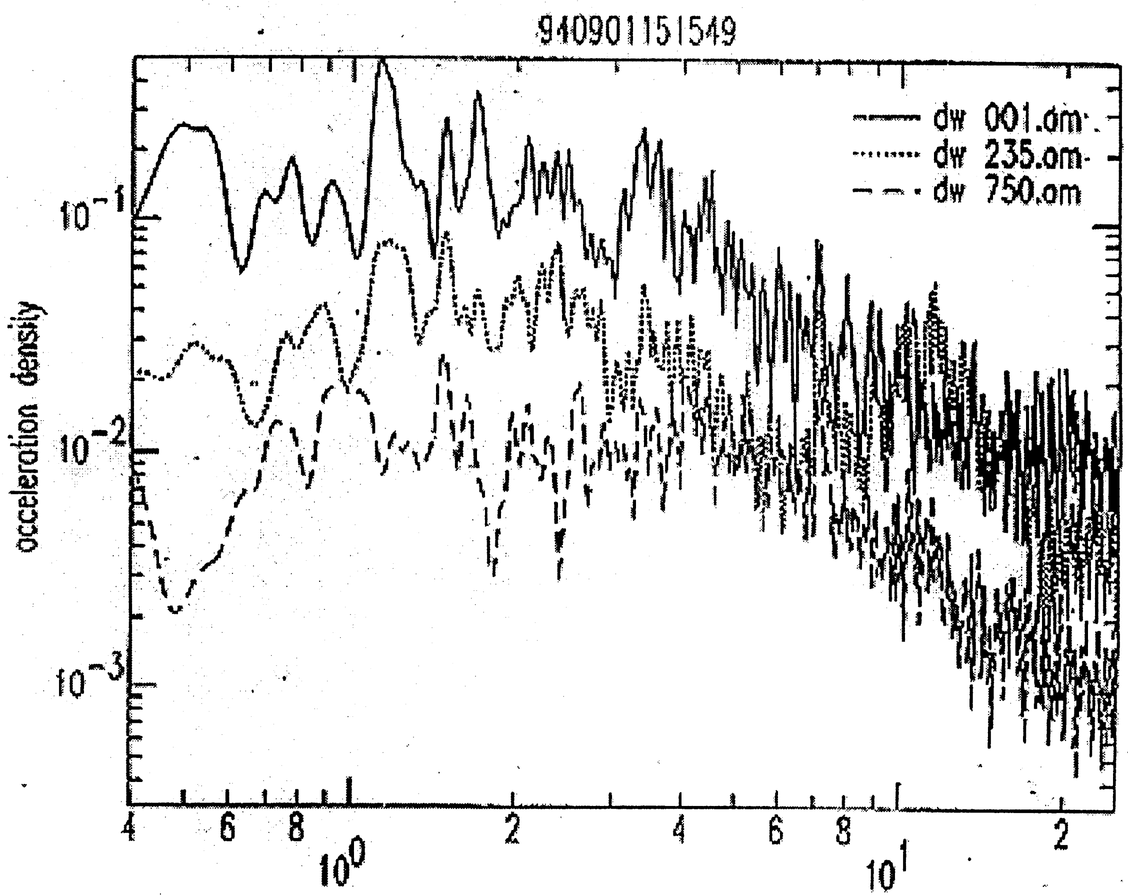


Figure 21: Spectra analysis of the eastern component from the top, middle, and bottom of the borehole on the Dumbarton Bridge.

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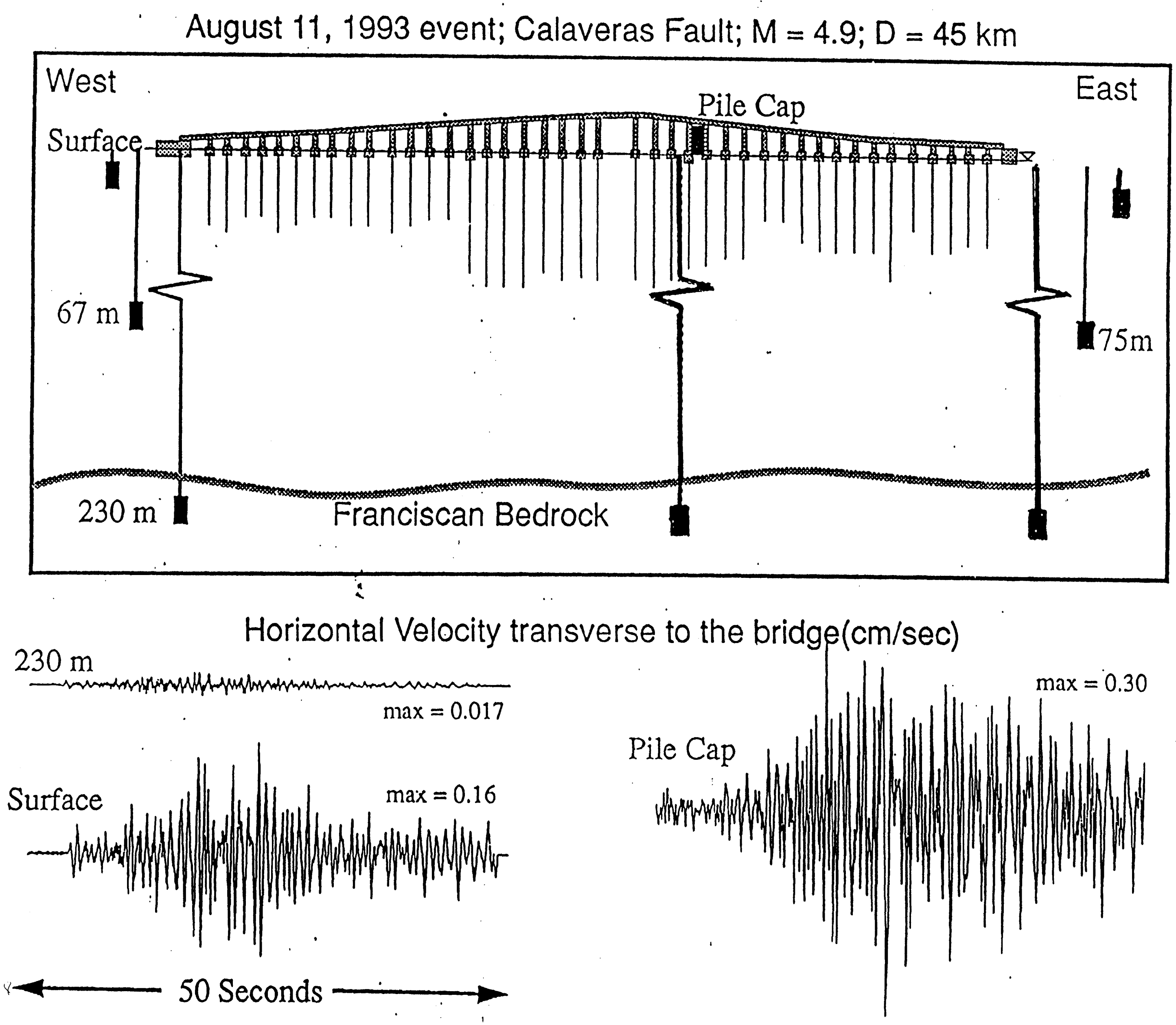

Figure 22: Recordings of acceleration from the top to the bottom of the borehole at pier 1 and from the top of the pile cap at pier 27 along the Dumbarton Bridge.